Renewable Energy 122 (2018) 265–274

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Techno-economic optimization for two SHPPs that form a combined system

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ARTICLE INFO

Article history:
Received 20 September 2017
Received in revised form
19 December 2017
Accepted 21 January 2018
Available online 1 February 2018

Keywords:
Energy efficiency
Small hydropower plant
Turbine
Optimization
Technical solution
Net present value

ABSTRACT

More pronounced climate changes and strict environmental requirements change the criteria used for the determination of the installation capacity and the turbine type for a small hydropower plant (SHPP). This paper proposes a technical solution that determines the optimal configuration for two existing SHPPs that operate in a combined system with the aim to increase the production of electricity during the flow rates lower than the minimum flow for which the supplier guarantees the turbine efficiency. When these two SHPPs with the installed capacities 1.220 MW and 1.327 MW and a common weir water intake, work as a combined system, a techno-economic optimization shows that the addition of a turbine in the downstream plant for flows smaller than 17% of the installation flow improves the electricity production. This nonlinear optimization problem is solved in the Matlab environment with constraints defined by applying the Active-Set algorithm. Based on the criterion of the maximum net present value (NPV), the techno-economic analysis shows that a less efficient but cheaper mechanical plant that comprises a less efficient turbine gives the highest NPV during the period of feed-in tariffs.
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1. Introduction

The Republic of Serbia was among 63 countries that globally had enacted feed-in policies as a support mechanism for electricity production from renewable energy in 2009 [1]. The milestone for the implementation of this kind of energy policy was the signing of the Treaty establishing the Energy Community [2]. By signing the Treaty, the Republic of Serbia accepted the binding obligation to increase the share of renewable energy in the final energy mix by 2020.

The establishment of legal framework [3–8], which is reviewed in detail in Refs. [9,10], and the implementation of feed-in tariffs resulted in the construction of 76 SHPPs with the gross installed capacity of 49.892 MW by the June 2017 [11]. The owners of all these SHPPs have acquired the status of privileged power producers for the period of 12 years.

The existence of inadequate cadaster of SHPPs, lack of experience of municipalities and designers in the field are difficulties that cause insufficient use of hydro potential. Hydrological studies, which are used for the determination of the installed capacity and the equipment selection for a SHPP, do not take into account the climate change and the occurrence of long draught periods. These difficulties are indirectly addressed in a specific problem that is being solved in the paper.

Fig. 1 schematically presents the existing state of the combined (coupled) system of small hydropower plants SHPP1 and SHPP2. Water from the weir intake is led by the penstock A to the first hydropower plant SHPP1, where, at the exit from the turbine, it directly flows into the penstock B and is led to the second hydropower plant SHPP2.

The maximal flow of both hydropower plants is 5.65 m^3/s. The gross head for SHPP1 is 34.50 m, and for SHPP2 37.76 m. The SHPP1 was put into operation in January 2014. At that time, the location for SHPP2 was not in the cadaster. The location was registered subsequently and SHPP2 started electricity production in 2016 when SHPP1 had already been used the status of privileged power producer for two years.

Each SHPP is equipped with one *Crossflow* turbine, and these two turbines, T1 and T2, have the same power of 1475 kW. The

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https://doi.org/10.1016/j.renene.2018.01.081
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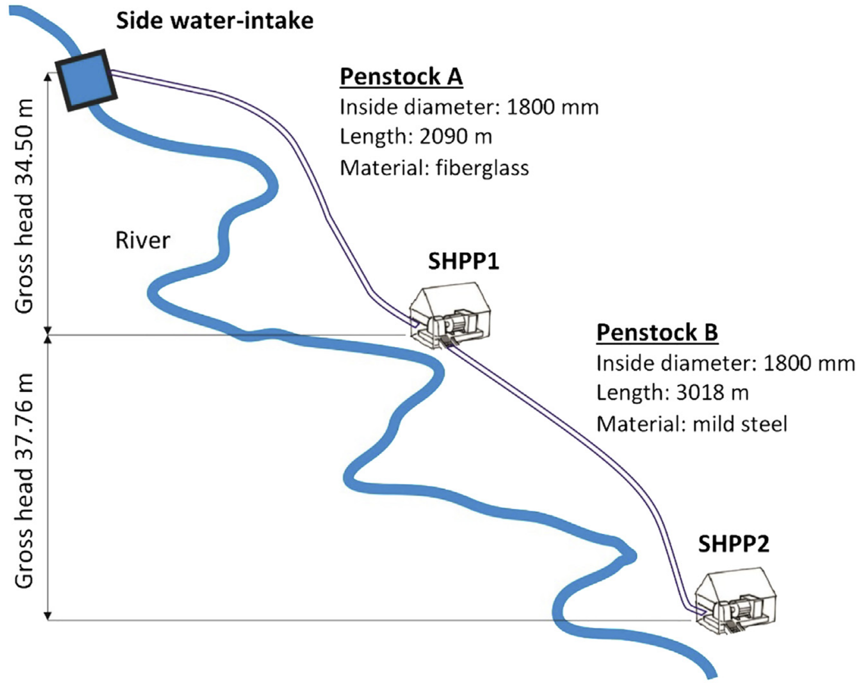

Fig. 1. Existing state.

experimental results obtained in exploitation conditions have shown a low degree of efficiency of the existing turbines at the flows smaller than 960 l/s (see Fig. 2). The limit noticed at 960 l/s represents 17% of the installation flow of the hydro power plant and the minimum flow for which the supplier of equipment guarantees the degree of efficiency of the turbine of 78%. During last couple of years, flow rates smaller than 960 l/s have been frequent during summer months.

This paper proposes a technical solution for two existing SHPPs that operate in a combined system with the aim to increase the production of electricity during the flow rates lower than the minimum flow for which the supplier guarantees the turbine efficiency. Three technical solutions are proposed for solving the problem. Each of the solution requires the installation of additional turbines, which would work independently or in parallel with the existing turbines at water flows smaller than 960 l/s. Fig. 2 shows also the efficiency of the additional turbine depending on the flow. The possibility to install the turbine parallel with the existing one was considered, and analyzed in Ref. [12], based on the techno-economic analysis, for the purpose of increasing energy efficiency. The difference in relation to [12] is that this paper considers the possibility of parallel and individual operation of two turbines, depending on the available water capacity.

To justify the investment into the reconstruction of the combined system, for each of the proposed solution, the optimal technical variant is chosen by a techno-economic analysis. The applied method of techno-economic optimization of turbine power is analogous to the optimization of capacity of wind turbines

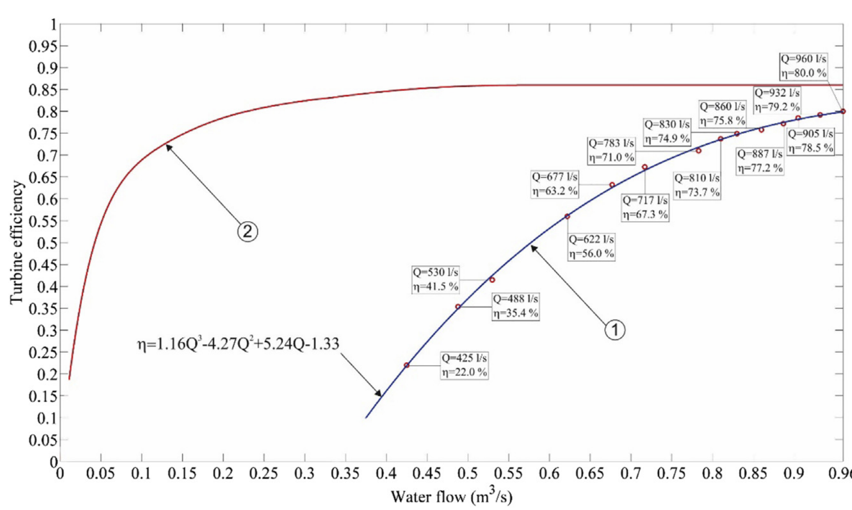

Fig. 2. The turbine efficiency depending on the water flow. 1 - is the approximation function obtained by the experimental data collected during the exploitation of the Crossflow turbine SHPP1 T1 at low flow rates. 2 - for the Crossflow turbine with the maximal installation flow of 960 l/s.

applied in the papers [13–17]. The nonlinear optimization problem in the mentioned references was solved by *MatLab* applying the *interior-point* method. In this paper, the *MatLab* program is also applied for solving the nonlinear optimization problem, but the *active-set* method is used. Techno-economic parameters of the net present value (NPV) and the analytical model for production of electricity from Refs. [18,19] are also applied in this paper for defining the objective function used for optimization.

2. Optimal SHPP configuration

2.1. Proposed technical solutions

To Increase the electricity generation in the combined system of power plants SHPP1 and SHPP2, at flows smaller than 960 l/s, three technical solutions are proposed.

The technical solution schematically shown in Fig. 3 foresees the installation of an additional turbine SHPP2 T2 with the accompanying equipment. The maximum flow for the turbine SHPP2 T2 would be 960 l/s, while the gross head would be 72.26 m and would represent the sum of gross heads for the power plants SHPP1 and SHPP2. At the occurrence of flows smaller than 960 l/s, it is foreseen that the existing turbines SHPP1 T1 and SHPP2 T1 will stop and that water will be directed to the turbine SHPP2 T2. Such a mode of operation would not lead to the increase in the installed power of the downstream plant, and hence there would be no reduction in the feed-in tariff in relation to the existing state. In order to allow the proposed configuration (see Fig. 3) to operate in the described manner, it is necessary to reconstruct the existing system (see Fig. 1): placement of an additional by-pass penstock C and a connecting penstock D with the diameter of 650 mm, installation of a butterfly valve BC2 DN 1800 at the penstock B, installation of a butterfly valve BC1 DN 650 at the penstock C, and installation of a turbine SHPP2 T2 with the accompanying generator and the control system (see Fig. 3). The mechanical plant with the turbine SHPP2 T2 can be accommodated by the existing facility SHPP2.

During the operation of the turbine SHPP2 T2, the butterfly valve BC2 at the penstock B is in the closed position.

Fig. 4 shows schematically the second technical solution. The solution foresees the installation of two additional turbines, SHPP1 T2 and SHPP2 T2, with the accompanying equipment, which would operate only at the flows smaller than 960 l/s and larger than the installation flow 5.65 m^3/s. The gross head for the turbine SHPP1 T2 would be the same as for SHPP1 T1, i.e. 34.50 m, while the gross head for the turbine SHPP2 T2 would be the same as for SHPP2 T1, i.e. 37.76 m. For realization of this technical solution, it is necessary to reconstruct the existing system: installation of the turbines SHPP1 T2 and SHPP2 T2 with the accompanying equipment, construction of additional penstocks C and D with the diameter of 650 mm, and construction of a facility for accommodation of the turbine SHPP1 T2 with the accompanying equipment. Installation of the turbines SHPP1 T2 and SHPP2 T2 provides the increase in the installed power of both power plants, so that lower feed-in tariffs were used in the analysis.

Fig. 5 schematically depicts the third technical solution, which foresees, in relation to the existing state, the removal of mechanical plants SHPP1 and SHPP2, joining penstocks A and B and their reconstruction, construction of a facility for a new mechanical plant and installation of new turbines. In this case, the gross head of the power plant would be 72.26 m. Having in mind the facts that the existing mechanical equipment installed in SHPP can be used only partly due to its specificities, the preliminary techno-economic analysis for the proposed technical solution 3 has shown that considerable investments in the new mechanical plant, the facility and reconstruction of the penstocks are not economical (the highest initial investment, and the lowest NPV), and that is why a detailed comparative analysis of technical solutions 1 and 2 will be presented in the continuation of the paper.

2.2. Techno-economic analysis of the proposed technical solutions

The data about the mean annual flow of the river based on measurements for the period 1946–2006 are used in this paper.

Fig. 6 presents the flow duration curve for the period of one year. The flow duration curve is defined by interpolation of the data about the probability of appearance of flow by means of a tenth-

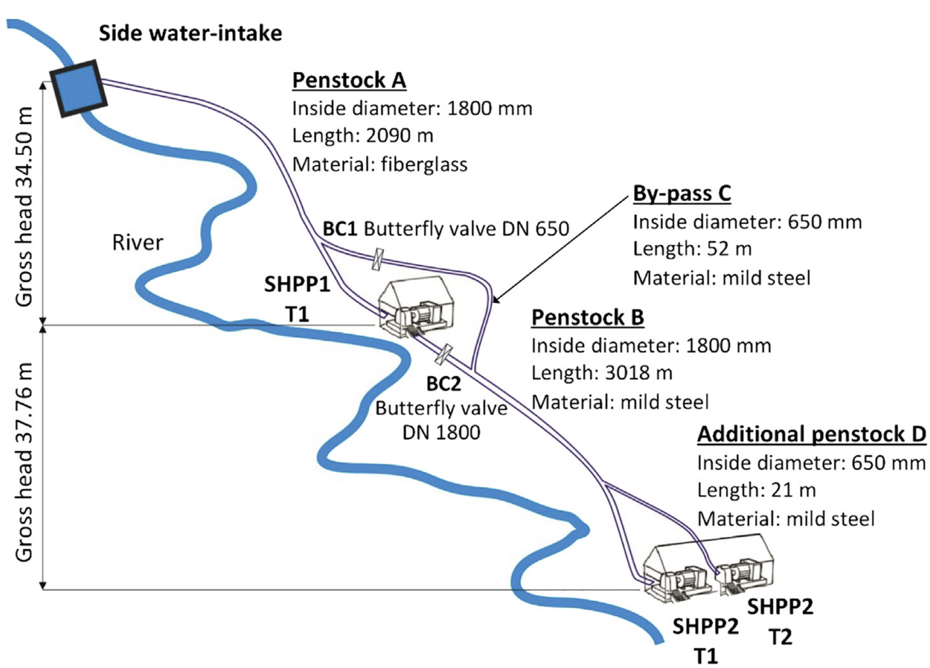

Fig. 3. Technical solution 1.

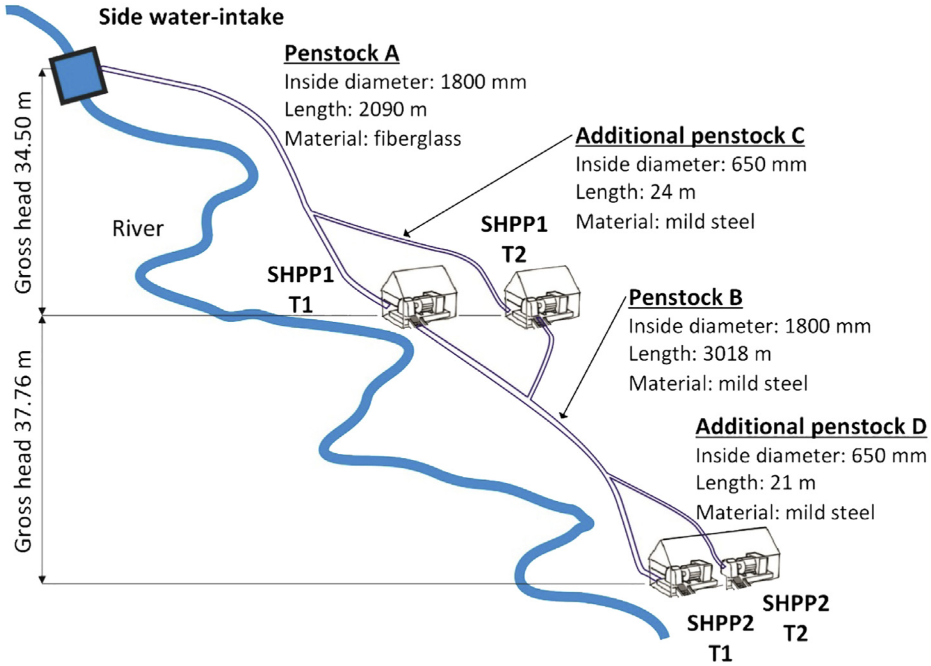

Fig. 4. Technical solution 2.

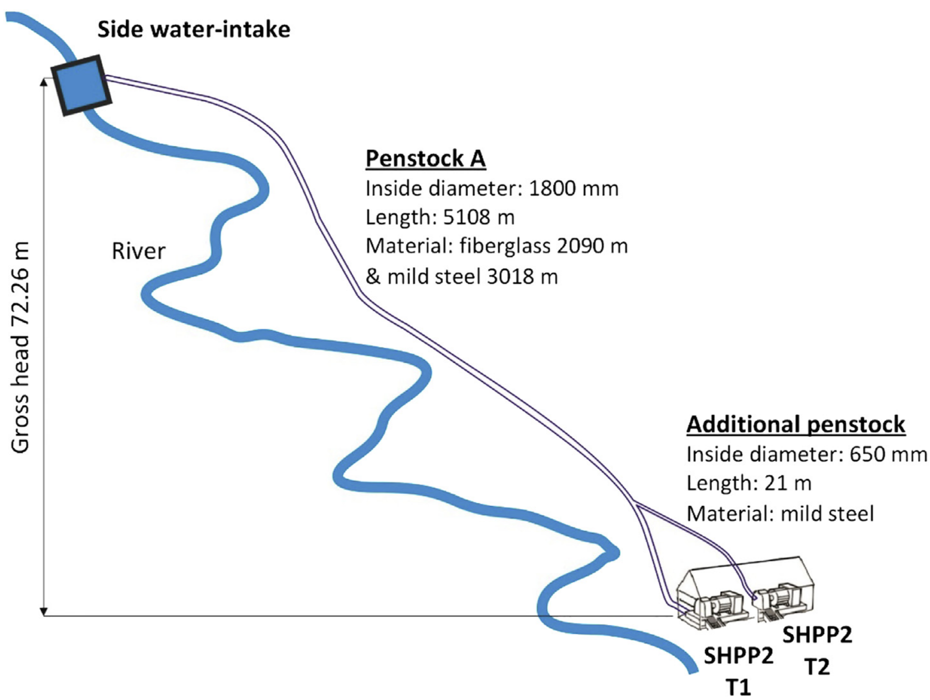

Fig. 5. Technical solution 3.

degree polynomial:

$$Q = \sum_{i=0}^{n} p_i z_i, \tag{1}$$

where:

$$z = (x - \mu)/\sigma, \text{and } p_0, \ \ldots, \ p_{10}, \ \mu, \ \sigma \text{ are constant.} \tag{2}$$

The part of the flow duration curve (see Fig. 6) at which operational problems of the existing combined system occur (see Fig. 7) is represented by Equations (1) and (2), with the condition:

$$68.43 \le x \le 100. \tag{3}$$

Figs. 6 and 7 present the flow duration curve during the year and the flow duration curve for small water flows of the river, respectively. To obtain the flow available for production of electricity, it is necessary to subtract the biological minimum $Q_{min} = 0.74\ m^3/s$

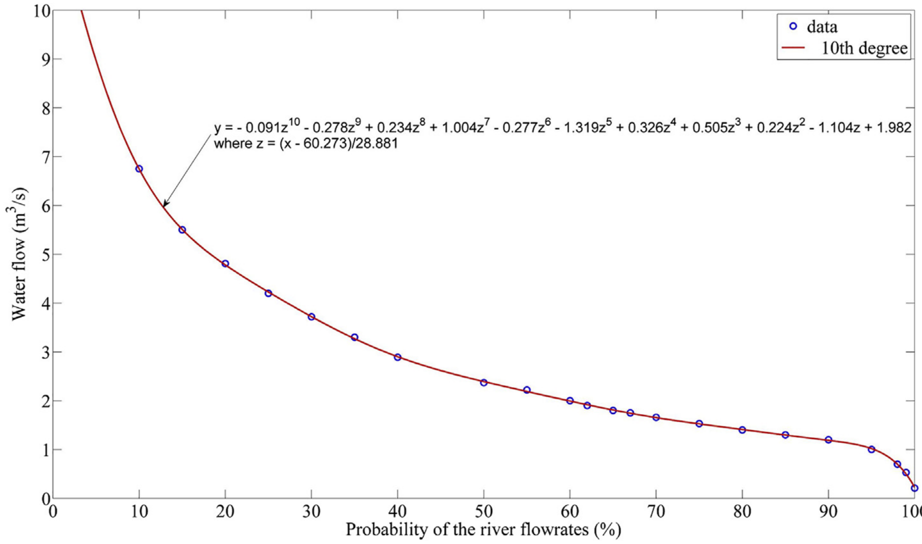

Fig. 6. Flow duration curve.

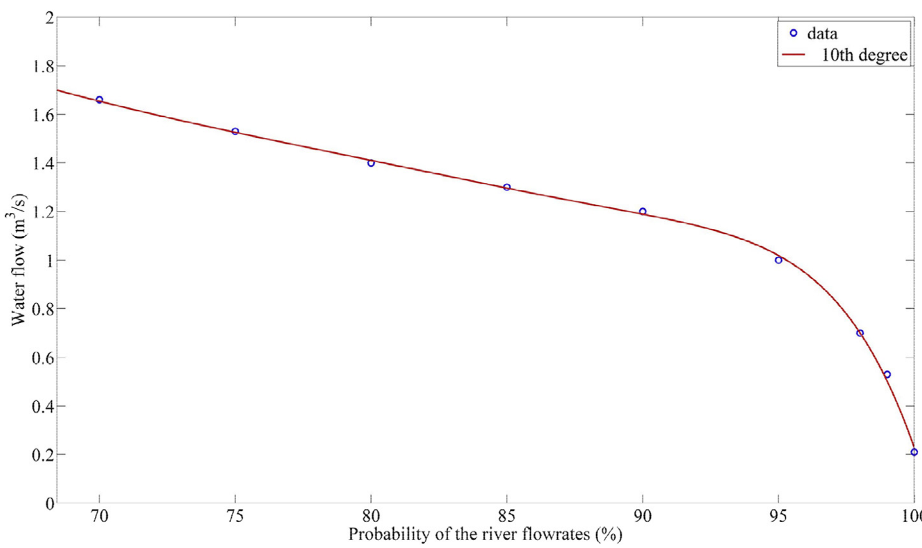

Fig. 7. Flow duration curve for small water flows of the river.

from the river flow:

$$Q_t = Q - Q_{min}. \tag{4}$$

The generated electricity can be defined in the following way:

$$E = \eta \rho g H_n Q_t T, \tag{5}$$

where η is the total degree of efficiency of the production of electricity (including the degree of efficiency of the turbine, the generator and the multiplier), ρ is the density of water, g is the acceleration of gravity, Q_t is the water flow through penstock defined by Eq. (4), T is the time for production of electricity expressed in working hours.

In Eq. (5), H_n represents the useful height difference for production of electricity. It can be defined as the difference between the gross head H_g and the loss δH:

$$H_n = H_g - \delta H, \tag{6}$$

where the head loss is calculated according to the Darcy-Weisbach equation [12]:

$$\delta H = \left(\lambda \frac{L}{d} + \sum \zeta \right) \frac{8 Q_t^2}{g \pi^2 d^4} \tag{7}$$

where L and d are the length and the inner diameter of the feed penstock, respectively, λ is the flow coefficient, and ζ is the minor loss coefficient.

The gross profit can now be expressed as the product of the total generated electricity E, defined in Eq. (5), and the feed-in electricity tariff P, defined by the Decree on Incentive Measures for Privileged Power Producers by the Government of the Republic of Serbia [20].

Investment costs of the reconstruction of the SHPPs cover the price of new turbines, reconstruction of the penstocks, installation of butterfly valves, and the costs of necessary construction works.

The economic parameter of the net present value (NPV) was proposed as a criterion for selection of the most favourable technical solution:

$$NPV = \sum_{i=1}^{t} \frac{C_{ni}}{(1+r)^i} - C_0, \tag{8}$$

where C_{ni} is the net cash inflow during the period i, C_0 the total initial investment costs, r the discount rate, i the number of time periods, t the observed time period. The net cash inflow C_{ni} is calculated when the maintenance costs C_{mi} and the exploitation costs C_{ei} are subtracted from the total gross income C_{gi}:

$$C_{ni} = C_{gi} - C_{mi} - C_{ei}. \tag{9}$$

The productivities of all turbines, the annual gross income, the investments, and the NPV for the period of 10 years for SHPP1 and 12 years for SHPP2 are calculated based on Eqs. (1)–(9).

2.3. Optimal SHPP configuration

Considering low flow rates (less than 960 l/s), which caused the problem, gross heads for the proposed technical solutions (34.50 m, 37.76 m, and 72.26 m see Figs. 3–5), and the recommendations from the literature [21–24], the appropriate commercial turbine types that could be implemented in the both analyzed configurations are Crossflow and Francis. The selection is carried out presuming that the optimal turbine type is Crossflow because: (i) compared with the Francis turbine, it has a smaller efficiency at the maximal flow (960 l/s), but a larger one at flow rates noticeably smaller than the maximal (see Fig. 7 and [21]), and (ii) the Francis turbine is not precisely the recommended choice for the flows lower than 960 l/s and gross heads 34.50 m and 37.76 m as can be seen in Refs. [25–27]. This presumption is verified in the remainder of the paper.

Table 1 shows that the proposed configuration 2 results in the largest total production of electricity of 9284.53 MWh, and, based on that, the largest gross income to the amount of 951000 €/year. On the other hand, configuration 1 results in the total production of 8994.44 MWh and the gross income of 935403 €/year, but according to the already defined criterion of maximum net present value (8) for the period of 10 years for SHPP1 and 12 years for SHPP2, and the discount rate of 5%, configuration 1 represents the more favourable solution. Such a result was achieved because configuration 2 requires investments which are by 2.13 times higher in relation to configuration 1. Table 2 shows the positive effect of reconstruction of the SHPPs for the most favourable case (technical solution 1) in relation to the existing state, where there are SHPP1 T1 and SHPP2 T1, which operate in the combined system.

Table 2 shows that for water flows smaller than 960 l/s, the use of the turbine SHPP2 T2 results in the increased production of electricity by 412.15 MWh in relation to the sum of production from turbines SHPP1 T1 and SHPP2 T1. The gross income from the use of configuration 1, according to the valid feed-in electricity tariffs defined in Ref. [20], is 42104 €/year. Based on these results, it is clear that the reconstruction of the hydro power plant is justified. It is necessary to determine the power of the turbine SHPP2 T2, which would operate in case of occurrence of flows smaller than 960 l/s. The criterion for selection of power of the turbine SHPP2 T2 was set in such a way as to accomplish the maximum financial gain. For that purpose, the optimization problem was set based on the techno-economic analysis of the hydropower plant and the maximum NPV for the period of subsidizing the production of electricity from renewable energy sources.

Table 2
Positive financial effect (of the technical solution 1).

	Production	Feed-in tariff	Gross income
	MWh	c€/kWh	€
SHPP1 T1	185	10.52	19458.9
SHPP2 T1	203.7	10.31	20996.5
SHPP1 T1 + SHPP2 T1	388.6	–	40455.4
SHPP2 T2	800.8	10.31	82559.7
Difference in production	412.1		
Difference in gross income			42104.4

Even the productivity of the optimal configuration could be a bit improved as the tailrace from the SHPP 2 allows the use of the kinetic energy of the discharge flow. To maximally use hydro potential an important topic in the ongoing research [28,29] is the recovery of flow conditions for downstream turbines. In this paper, this topic is only briefly analyzed. The discharge from SHPP 2 is collected and lead through an open canal with the cross section 3 × 1.1 (height of water) m. Not to affect the effective head on the turbines, the canal allows the use of two 1.2 × 1.1 m reaction turbines [30] in front of its mouth. These turbines would have the maximum useful power output of 6.46 kW, and would annually produce 15.24 MWh/year of electricity.

3. Optimization of turbine power

The aim of this paper is to define the optimum power of hydropower turbines for two proposed configurations of the SHPPs. For that purpose, the optimization problem was formed with the maximum NPV as the objective function. The optimization periods are 10 and 12 years for SHPP1 and SHPP2, respectively.

3.1. Objective function

As it has been previously stated, the objective function of the

Table 1
Selection of the optimum configuration (A = 10 for SHPP1 T1 or A = 12 for other turbines).

Technical solution			1	2
Production	SHPP1 T1	MWh	3846.1	3826.7
	SHPP1 T2	MWh	/	529.5
	SHPP2 T1	MWh	4344.3	4354.5
	SHPP2 T2	MWh	804.1	573.9
Feed-in tariff for SHPP1 T1 and SHPP1 T2		c€/kWh	10.52	10.28
Feed-in tariff for SHPP2 T1 and SHPP2 T2		c€/kWh	10.31	10.21
Gross income		€/Year	935403.6	950999.8
Investment		€	251000	535203
Net present value	Period	Year	A	A
	Discount rate	%	5	5
	NPV	€	7185177	7058912

given problem is to maximize the NPV:

$$f = \max(NPV), \tag{10}$$

where the NPV is defined by Eqs. (8) and (9).

3.1.1. Net cash inflow

The net inflow defined by Eq. (9) represents the total gross income realized by the production of electricity C_{gi}, with the maintenance costs C_{mi} and the exploitation costs C_{ei} subtracted. The total generated electricity defined by Eq. (5), delivered to the electric power system, according to the defined feed-in tariff in Ref. [20], represents the gross income of the SHPP. The expenses in operation of the SHPPs cover the exploitation costs C_{ei} and the maintenance costs C_{mi}. The maintenance costs can be represented by a linear function depending on the turbine power:

$$C_{mi} = d_1 P_t + d_2, \tag{11}$$

and the exploitation costs can be represented by a linear function depending on the working hours:

$$C_{ei} = lT, \tag{12}$$

where d_1, d_2, and l are constants.

3.1.2. Initial investment

The total initial investment costs C_0 cover: the price of new turbines, the price of reconstruction of penstocks, and the price of necessary construction works. The prices of turbines depending on power were modelled by a quadratic function, based on the data obtained by manufacturer [34]:

$$C_0 = s_1 P_t^2 + s_2 P_t + s_3, \tag{13}$$

where s_1, s_2, and s_3 are constants.

Investment costs for the construction works and necessary reconstruction of the penstocks are calculated as estimated fixed costs.

Based on Eqs. (1–13), the objective function f can be defined aiming at the maximum NPV, for the period of 12 years, with a discount rate of $r = 5\,\%$ annually:

$$f = max\left[-C_0 + (EP - C_{mi} - C_{ei}) \sum_{i=1}^{12} \frac{1}{(r+1)^i} \right], \tag{14}$$

i.e.:

$$f = max\left[-s_3 - (d_2 + d_1 P_t + l\sigma_1 - \eta_R P \eta_G P_t \sigma_1) \sum_{i=1}^{12} \frac{1}{(r+1)^i} - s_2 P_t - s_1 P_t^2 \right], \tag{15}$$

where:

$$\sigma_1 = t_2 + t_1 z, \tag{16}$$

and σ_1 represents the linear change of time T.

3.2. Constraints

The given optimization problem is constrained by linear equalities and inequalities, as well as by nonlinear equalities and inequalities, and the boundaries of intervals.

3.2.1. Linear inequalities

This type of constraints can be presented in a general form in the following way:

$$Ax \le b,\ A \in R^{m \times n},\ x \in R^{n \times 1},\ b \in R^{m \times 1}. \tag{17}$$

In the observed optimization problem, the previous inequality can be represented in the following way:

$$\begin{bmatrix} t_1 & 0 & 0 & 0 & 0 & -1 \\ \alpha_{11} & 0 & -1 & 0 & 0 & 0 \\ \alpha_{12} & 0 & -1 & 0 & 0 & 0 \\ \alpha_{13} & 0 & -1 & 0 & 0 & 0 \\ \beta_{11} & 0 & 0 & -1 & 0 & 0 \\ \beta_{12} & 0 & 0 & -1 & 0 & 0 \\ \beta_{13} & 0 & 0 & -1 & 0 & 0 \end{bmatrix} \begin{Bmatrix} z \\ Q_t \\ \eta_T \\ \eta_G \\ P_t \\ T \end{Bmatrix} \le \begin{Bmatrix} -t_2 \\ \alpha_{21} \\ \alpha_{22} \\ \alpha_{23} \\ \beta_{21} \\ \beta_{22} \\ \beta_{23} \end{Bmatrix}, \tag{18}$$

where α and β represent the coefficients of linear functions used for approximation of nonlinear dependencies of the degree of efficiency of the turbine and the generator depending on the flow, respectively. More information about linear approximation of nonlinear functions can be found in reference [31].

3.2.2. Linear equations

This group of constraints can be presented in a general form in the following way:

$$A_{eq} x = b_{eq},\ A_{eq} \in R^{m \times n},\ x \in R^{n \times 1},\ b \in R^{m \times 1}, \tag{19}$$

i.e. for $m = 1$ and $n = 6$:

$$\begin{bmatrix} \gamma_1 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} z \\ Q_t \\ \eta_T \\ \eta_G \\ P_t \\ T \end{Bmatrix} = \gamma_2. \tag{20}$$

The previous equation defined the linear dependence between the flow Q_t and the auxiliary variable z.

3.2.3. Nonlinear inequalities

This group of constraints can be presented in a general form in the following way:

$$c(x) \le 0, \tag{21}$$

i.e. for the given optimization problem:

$$Q - Q_{max} \le 0, \tag{22}$$

$$Q_t - Q + Q_{min} \le 0, \tag{23}$$

$$\delta H - \delta H_{max} \le 0, \tag{24}$$

$$\delta H - H_g \le 0. \tag{25}$$

Fig. 8 presents the head loss from Eqs. (24) and (25) calculated based on Eq. (7). It shows the head loss for configurations 1 and 2 for small water flows ($0 - 1\ m^3/s$).

Fig. 9 presents the head loss for configuration 3, calculated based on Eq. (7).

Based on Eq. (1) in which the flow is defined as a nonlinear function, Eqs. (22) and (23) are nonlinear, too. Eqs. (24) and (25) are nonlinear because of the head loss δH (see Figs. 8 and 9) defined by

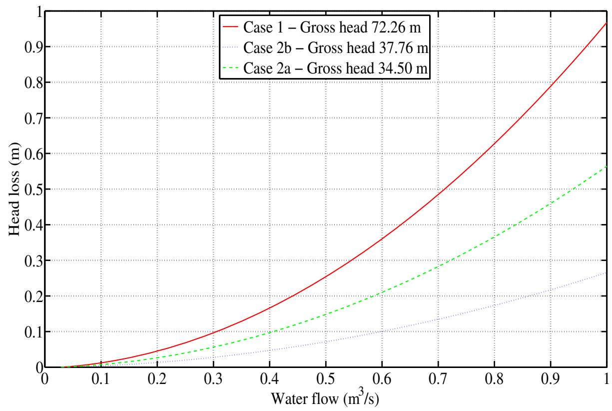

Fig. 8. Head loss for small water flows.

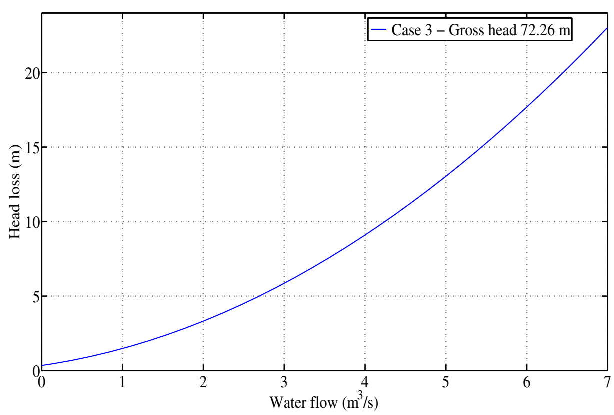

Fig. 9. Head loss for large water flows.

Eq. (7).

3.2.4. Nonlinear equations

This group of constraints can be presented in a general form in the following way:

$$c_{eq}(x) = 0, \tag{26}$$

i.e. for the given optimization problem:

$$P_t - Q_t H_n \eta_T g = 0. \tag{27}$$

Eq. (27) is nonlinear based on the definition of the flow Q_t using Eqs. (1) and (4), as well as based on the definition of the net head H_n using Eqs. (6) and (7).

Finally, the optimization problem defined by Eqs. (14–27) is obtained and it consists of the nonlinear objective functions Eqs. (14) and (15), as well as of linear and nonlinear constraints defined by Eqs. (17–27). In order to solve the given optimization problem, the *MatLab* environment was used for nonlinear optimization with constraints defined by applying the *Active-Set* algorithm [32,33].

3.3. Optimization results

Table 3 presents the results of optimization of turbine power based on the criterion of maximum NPV for the period of subsidizing the production of electricity from renewable energy sources in the Republic of Serbia (12 years) and the discount rate of 5% annually. The initial technical parameters, the installed flow and the gross head, are given for two proposed configurations of SHPPs.

Table 3 shows that the optimization resulted in the power of the turbine SHPP2 T2 of 520.95 kW for technical solution 1. For technical solution 2, the obtained power of the turbine SHPP1 T2 is 249.65 kW and the obtained power of the turbine SHPP2 T2 is 271.76 kW.

4. Selection of turbine type

In Section 2, the most favourable technical solution for reconstruction of the SHPP was selected based on the criterion of maximum NPV. It is technical solution 1, which foresees the installation of a small turbine in the downstream plant of the SHPP 2. That new turbine would operate in case of appearance of flows smaller than 960 l/s. The gross head of the turbine SHPP2 T2 would be 72.26 m. In Section 3, optimization of the necessary power of the turbine SHPP2 T2 was performed for case 1, which is 520.95 kW (Table 3, case 1). The turbine power of 520 kW was adopted.

The next step is the selection of turbine type SHPP2 T2 for the gross head of 72.26 m and the maximum flow of 960 l/s. According to [12], three types of turbine are analyzed: Crossflow, Pelton, and Francis.

From Table 4 it is obvious that the turbine SHPP2 T2 with the power of 520 kW, type Francis, accomplishes higher electricity generation in relation to the turbines type Pelton and Crossflow. Compared with the implementation of turbine SHPP2 T2 type Pelton and Crossflow, the use of the turbine type Francis would increase the positive financial effect by 1.10% and 7.78%, respectively. On the other hand, the investment for the procurement and installation of equipment and reconstruction of the facility for accommodation of the mechanical plant with the turbine SHPP2 T2 is smallest in the case of installation of the turbine type Crossflow, i.e. it is 251000 €, whereas the plant with the turbine type Pelton is by 32% more expensive, and with the turbine type Francis by 52% more expensive. The main reason for the expressed differences in the costs of plants is the fact that the turbine type Crossflow can be installed in the existing mechanical plant SHPP2 T1 with minimum financial investment, while for the installation of Pelton and Francis turbines with the accompanying equipment it is necessary to build special facilities. The criterion for selection of turbine type SHPP2 T2 is the maximum NPV defined by Eq. (8). Based on this criterion, the most favourable solution is the plant with turbine type Crossflow with the NPV of 144442 € for the period of 12 years and the discount rate of 5%.

5. Conclusions

The paper for two existing SHPPs that operate as the combined system addresses the problem of reduced electricity production that occurs during the flow rates lower than the minimum flow for which the supplier guarantees the turbine efficiency. To increase the electricity production of the combined system for flow rates smaller than 960 l/s, three possibilities for reconstruction of the SHPPs were proposed, and a detailed techno-economic analysis was performed for two technical solutions. Both variants foresee the installation of turbines with small capacities, aiming at increasing the degree of efficiency of electricity generation. The net present value was used as the criterion for selection of the optimum configuration. According to that criterion, the maximum NPV of 7185177 € for the period of 12 years is accomplished with configuration 1. This solution leads to the increase in the production of electricity by 412.15 MWh at the annual level, which represents the increase in income by 42104 €/year. After that, optimization of the necessary power of turbines was performed based on the techno-economic analysis and the maximum NPV as the objective

Table 3
Optimization results.

		Technical solution 1	Technical solution 2	
		SHPP2 T2	SHPP1 T2	SHPP2 T2
Installed water flow	m^3/s	0.96	0.96	0.96
Gross head	m	72.3	34.5	37.8
max NPV	€	354120	173237	181999
Power of turbine	kW	521	249.7	271.8

Table 4
Selection of turbine type SHPP2 T2.

Type of turbine SHPP2 T2 (Gross power 520 kW)			Crossflow	Pelton	Francis
Production of turbine SHPP2 T2		MWh	804.1	835.4	840.6
Production at small water flows at SHPP1 T1 and SHPP2 T1		MWh	371.3	371.3	371.3
Increase in production by using turbine SHPP2 T2		MWh	432.7	464.1	469.3
Feed-in tariff		c€/kWh	10.31	10.31	10.31
Positive effect of installation of SHPP2 T2		€/Year	44615	47846	48380
Investment		€	251000	331100	382480
Net present value	Period	Year	12	12	12
	Discount rate	%	5	5	5
	NPV	€	144442	92977	46330

function. For solving the given optimization problem, the *MatLab* environment was used for nonlinear optimization with constraints defined by applying the *Active-Set* algorithm. For the selected most favourable configuration 1, the optimization resulted in obtaining the power of the turbine SHPP2 T2 of 520.95 kW. The turbine power of 520 kW was adopted. At the end, the type of turbine SHPP2 T2 was selected based on the criterion of maximum NPV. The Crossflow turbine with the power of 520 kW was selected, which leads to the largest financial gain of 144442 €.

The hydropower potential of the selected location for SHPPs defined by the flow duration curve and the net head, which is defined by the gross head and the penstock characteristics (diameter, length, material, route) together with the economical parameters defined by the duration and the value of feed-in tariffs and the total investment determine the type of the selected turbine. The techno-economic analysis for the optimal solution has shown that a less efficient but cheaper mechanical plant that comprises a Crossflow turbine gives the highest NPV during the period of feed-in tariffs.

Acknowledgements

This work was conducted within the project TR 33027 supported by the Ministry of Education, Science and Technological development of the Republic of Serbia.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.renene.2018.01.081.

Nomenclature

Q	water flow, m^3/s
$p_0, \ldots, p_{10}, \mu, \sigma$	constants for interpolation of data about the probability of appearance of flow,
x	probability of appearance of flow, %
Q_t	water flow available for production of electricity, m^3/s
Q_{min}	biological minimum of flow, m^3/s
E	- generated electricity, kWh
η	total degree of efficiency of electricity generation,
ρ	density of water, kg/m^3
g	acceleration of gravity, m/s^2
T	electricity generation time, h
H_n	net head, m
H_g	gross head, m
δH	head loss, m
L	- length of penstock, m
d	inner diameter of pipes, m
λ	flow coefficient,
ζ	minor loss coefficient,
P	feed-in electricity tariff, c€/kWh
C_{ni}	net cash inflow, €/year
C_0	total initial investment costs, €
r	discount rate, %
i	number of time periods,
t	observed time period, year
C_{gi}	total gross income, €/year
C_{mi}	maintenance costs, €/year
C_{ei}	exploitation costs, €/year
P_t	turbine power, kW
d_1, d_2	constants for modelling maintenance costs,
l	constant for modelling exploitation costs,
s_1, s_2, s_3	constants for modelling initial investment costs,
t_1, t_2	constants of linear change of time of electricity generation,
α	coefficient of linear functions for approximation of nonlinear dependencies of the degree of efficiency of the turbine depending on the flow,
β	coefficient of linear functions for approximation of nonlinear dependencies of the degree of efficiency of the generator depending on the flow,
Q_{max}	maximum water flow, m^3/s
δH_{max}	maximum head loss, m

Acronyms

SHPP	small hydro power plant
SHPPs	small hydro power plants
SHPP1	small hydro power plant 1
SHPP2	small hydro power plant 2
NPV	net present value
BCR	benefit/cost ratio
IRR	internal rate of return
SHPP1 T1	turbine 1 of small hydro power plant 1
SHPP1 T2	turbine 2 of small hydro power plant 1
SHPP2 T1	turbine 1 of small hydro power plant 2
SHPP2 T2	turbine 2 of small hydro power plant 2
BC1	butterfly valve DN 1100
BC2	butterfly valve DN 1800

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